



Status of Current Hopper and Bin Measurement Technologies

PURPOSE: Research to improve dredging contract management, economics (cost optimization), and contaminated sediments management (document dredging and placement locations) is currently being conducted by the Innovative Technologies (IT) Focus Area of the U.S. Army Corps of Engineers (USACE) Dredging Operations and Environmental Research (DOER) Program. A common element in these research efforts is the ability to measure dredge production with the Silent Inspector (SI). This technical note (TN) describes currently used hopper and bin production measurement methods and discusses their respective capabilities and limitations. In this TN, the term hopper is defined as the holding space for dredged material in a hopper dredge, and the term bin identifies the holding space of a barge or scow. Subsequent DOER technical notes will refer back to this document as a basis for defining system requirements in the development of improved hopper and bin measurement technologies.

BACKGROUND: The DOER Innovative Technologies Focus Area is currently conducting research to develop and demonstrate robust hopper and bin instrumentation and data analysis techniques to quantify dredged material for assessing dredge performance. Corps dredging operations are in transition to automated monitoring of contract dredge operation (Rosati 1998, Welp and Rosati 2000, Rosati and Prickett 2001). The routine use of Silent Inspector (SI) data has focused attention on the accuracy of production measurement. Analysis of hopper dredge total production data errors clearly indicates that the largest uncertainty is measurement of dredged material in the hopper (Rullens 1993, Rokosch 1989, Scott 2000). The U.S. Army Engineer Research and Development Center (ERDC) worked with USACE Districts and dredging contractors to investigate the performance of existing hopper and bin measurement systems. Results from this investigation are being used to define a set of system requirements for improving hopper and bin measurement.

In addition to hydrographic surveying before and after dredging, there are two ways of determining hopper dredge production: measurement in the pipeline and measurement in “means of conveyance” (Rullens 1993). Production is based on the quantity of solids transported by the dredge. Production determined by hydrographic survey provides performance quantities relative to the sediment’s in situ mass characteristics (i.e., bulk density, etc.). It is desirable to relate quantities of solids measured in the pipeline and means of conveyance to the “in situ solids quantity,” but sediment bulking influences these relationships.

A bulking factor is the ratio of the volume occupied by a given mass of dredged material in either a hopper or bin immediately after deposition by a dredging process, to the volume occupied by the same mass of sediment in situ. Sediment material, mass, and behavior characteristics, and different types of dredges and dredging techniques affect bulking. Granular materials may increase or decrease volume, depending on the initial density state (loose or

dense) and the final deposition manner. Cohesive soils tend to increase in volume when removed from their in situ position. Hydraulic dredges usually bulk up sediment more than mechanical dredges due to water entrainment. New work material tends to have higher initial bulking in the placement area than maintenance material because it is usually in a more consolidated in situ state. A general rule of thumb is the larger the grain size, the lower the bulking factor (for relative approximations, sand can bulk up 1.0 to 1.2, silt 1.2 to 1.8, and clay 1.5 to 3.0 (USACE Dredging Fundamentals PROSPECT Course, 1998)).

Measurement in the pipeline consists of an inline production meter that measures the slurry flow velocity and density before it enters the hopper. Measurement in the means of conveyance involves determining the volume and/or weight of the hopper load. Several American dredges measure one or the other of these parameters to quantify production, but most U.S. hopper dredges measure both to calculate the load's average density or some derivative thereof, i.e., tons dry solids (Welp and Rosati 2000). Various methods (described later in this technical note) are used to measure the hopper load weight and volume. Determining barge production by "measurement in the bin" usually involves quantification of bin load volume. Bin load weight is also used as a production parameter on barges, but on a more limited basis. This technical note describes these different measurement methods and discusses their respective advantages and disadvantages, capabilities, and limitations.

MEASUREMENT IN THE PIPELINE: A "measurement in the pipeline" dredge production meter is a system that determines slurry velocity and density, and uses these two values to calculate dredge production. The system usually consists of a density meter, flow meter, data recorder, and an output display that indicates production in units of mass or volume per unit time. The major types of flowmeters used on hopper dredges include electromagnetic and Doppler acoustic devices, while slurry density is usually measured by a nuclear density device.

The electromagnetic flow meter works on the principle of electromagnetic induction and is designed to measure the flow of conductive liquids in a pipe. Two electromagnetic coils surround a pipe made of anti-magnetic materials and produce a magnetic field at right angles to the flow direction. As a conductive liquid passes the metering section, the lines of force from the magnetic field are cut, producing a low-level voltage at the stainless steel pick-up electrodes. The electrodes measure the potential difference, which is proportional to the flow rate and independent of the solids concentration (Herbich et al. 1992). The Doppler flow meter uses the theory of the 'Doppler effect'; i.e. there is an apparent change in the frequency of sound, light, or radiowaves as a function of motion. These meters consist of a piezoelectric crystal transducer, a Doppler frequency receiver, and a transmitter. The transmitter sends a continuous ultrasonic signal at an angle to the direction of flow through the pipe wall and into the liquid stream. The sound waves are reflected back to the receiver by particles, bubbles, or other discontinuities in the liquid. The difference between the transmitted and the reflected frequencies, called the 'Doppler shift,' is analyzed and the flow rate of the slurry is displayed (Herbich et al. 1992). The nuclear density gauge (Figure 1) measures density using the energy-absorption method. A radioactive source emits gamma-ray energy through the discharge pipe. The rays are absorbed in proportion to the density of the slurry, and a detector handles the gamma ray energy. The transmitted energy is finally converted into a linearized output, which indicates density changes.

A Nuclear Regulatory Commission (NRC) license is required to supervise the use of the nuclear density gauge (Herbich et al. 1992).

This production metering system has a number of different output indicators, but usually features a display combining both slurry velocity and slurry density. The data from the flow meter (which measures the total rate of slurry flow), and the density meter (which measures the specific gravity of the pumped mixture) are fed into the production metering system. It indicates the instantaneous total rate of solids flow per unit time in a variety of output parameters per unit time i.e., cubic meters (or yards) per



Figure 1. Nuclear density meter

hour, tons per hour, etc. It can also include a ‘totalizer,’ which gives a continuous indication of total production (project total or shift total), eliminating the need for post-operation computations to determine the total production (Herbich et al. 1992). The capability to calculate instantaneous and total quantities allows dredge production meter values to be used as an aid in optimizing dredge operation and production (Pankow 1989). These capabilities allow it to be integrated into an automated monitoring system i.e., the Silent Inspector (Rosati and Prickett 2001).

ERDC conducted laboratory studies (Pankow 1989) on production meter components. Several density gauges and flow meters manufactured by different companies were evaluated for accuracy and reliability in a closed test loop. Different grain-size materials, slurry concentrations, and velocity regimes were utilized for the study. General conclusions from the study were:

- The most accurate¹ flowmeters tested were, in decreasing order, electromagnetic and Doppler.
- Readings among the density gauges and the control density meter were almost identical.
- Readings among the magnetic flowmeters and the control flow meter were very similar.
- Readings among the Doppler flowmeters and the control flowmeter were significantly different.
- The preferred pipe orientation for both density gauge and flowmeter is vertical, but a horizontal pipe is acceptable by avoiding high slurry concentrations that produce a stationary or sliding bed with dune formation. The difference between vertical and horizontal orientation is on the order of 1 percent for the density gauge, 3 percent for the magnetic flowmeters, and 5 percent for the Doppler flowmeters.

¹ Accuracy is defined here as the agreement between a measurement and an accepted reference value that, when applied to a set of measurements, involves a combination of random and systematic components.

- Sand slurry flow results were more consistent and accurate than those for gravel.
- The Doppler meters produced higher values than the control meter at low slurry velocities but fell off significantly at higher slurry velocities, producing much lower values than the control.
- The most critical element in the use of production meters is the calibration of the individual components.

A “pipeline” production meter system was temporarily installed on the dustpan dredge *Jadwin* to evaluate the reliability and repeatability of the system and components (Pankow 1989) where the data proved consistent and reasonable. Scott (1992) summarizes the testing and evaluation of a production meter (electromagnetic flowmeter and nuclear density meter) installed on the hopper dredge *Wheeler* while dredging in fine-grained sediment. This study indicated that, provided the density and flow meters are calibrated and maintained, reliable, accurate density determination in the pipeline is possible when dredging silts. The study concluded that use of production meters for calculating production on a load-to-load basis may be limited due to overflow and leakage through the hopper doors, but for calculating the total production of dredged material through the pipeline for a given project, production meters can provide a reliable and accurate measurement of dredge production (Scott 1992).

Rullens (1993) states that an accuracy of 2 to 3 percent can be obtained under ideal conditions with calibrated instruments (electromagnetic flowmeter and nuclear density meter) and an inverted u-tube pipeline configuration. However, space restrictions onboard hopper dredges usually preclude the use of this optimum pipeline configuration. Additional error components include:

- Presence of gas in the slurry.
- Flow that falls below critical velocity value for stationary deposition.
- Use of an integration method over a period of time that multiplies measurement errors.
- Difficulty in calibrating systems.
- Very rapid variations in density and velocity in the pipe.
- Presence of debris.
- Wear and tear.

Rullens concludes that the velocity and density measurement method should only be used to ensure optimum production in the dredging cycle of a hopper dredge under two conditions:

- When in situ sediment density is very difficult to establish.
- When overflow is used, but overflow losses are not measured.

Accurate measurement of in situ sediment density is essential for the accurate calculation of volumetric production (Scott 2000). When the overflow method is used to optimize dredge production it is impossible to measure absolute production of the dredge; the measurement of velocity and density only gives relative information about the quantity and quality of the dredged material (Rullens 1993).

MEASUREMENT IN THE MEANS OF CONVEYANCE: Basically two parameters are measured to quantify hopper load contents: volume and weight. Either one of these two parameters is used as a production evaluation tool, or both are measured simultaneously to calculate the dredged material's average density or some derivative thereof (i.e., tons dry solids). Methods and equipment used to measure these parameters range from manually sounding the hopper volume with a weighted tape, to measuring and calculating hopper density with an automated measuring/monitoring system i.e., the Silent Inspector.

Volumetric Measurement

Hopper manual sounding methods. Since the first hopper dredge, the *General Moultrie*, was used to dredge the Charleston, South Carolina Bar in 1857, the volume of material in the hopper has been measured to calculate production (the *General Moultrie* with a 19-in.-diam drag pipe averaged 328 yd³ per day). Sounding of the hopper at various locations with a lead line was the primary method of measuring the volume of material being transported in the hopper, and this method is still in use today (see Figure 2).

This photograph was taken on a hopper dredge working in coarse-grained material ([medium-sized sand](#)) on the Columbia River Bar, managed by the Portland District. Soundings, or ullage measurements, are usually taken at six to eight different locations around the hopper using conveniently located reference points (i.e., walkways or coaming tops). The soundings are then averaged together. The resulting value is applied to an ullage table or equation that equates ullage distance to volume of material in the hopper. Depending on the number of soundings taken and care taken by the sounder, this measurement method can be quite accurate as long as the dredged material provides a surface with sufficient bearing strength to support the sounding lead (i.e., in a sand load). After loading is completed and the sand settles out quickly with a layer of water over it, this measurement method compensates for the water layer by the lead penetrating through the water layer till it rests upon the sand surface. Rullens (1993) concludes that when sand is dredged, the half-sphere "sounding" method (a sounding lead with specific mass and dimensions that will be described later) gives an unambiguous indication of the top of the solids mass and that this method is suitable to measure payable dredged quantities. Another advantage of this method is that the measuring equipment is inexpensive and simple. Disadvantages of the half-sphere sounding method include:

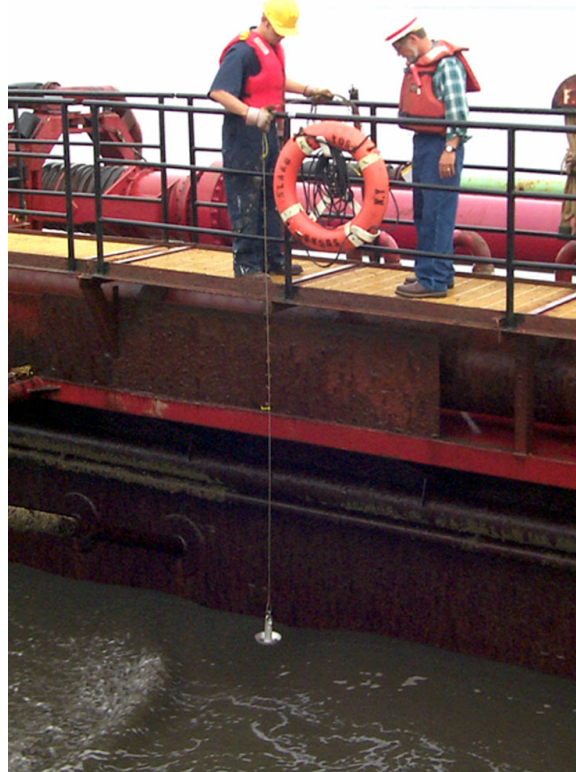


Figure 2. Sounding hopper to measure load volume

- The operations manual and the accuracy of measurements is affected by human influence.
- This manual operation is not conducive to automated monitoring systems like the Silent Inspector.

As the hopper load's consistency (resistance to deformation) decreases and becomes more "fluid" when dredging finer-grained material, the bearing strength can also decrease. When a sounding lead is applied in these loads, it starts to sink down into the material and greater measurement error is incurred because the solids above the lead are not accounted for. One effort to account for the mass of solids above the sounding lead is described in the following procedure describing hopper measurement from the USACE document

The Hopper Dredge, Its History, Development, and Operation, 1954, (also known as "The Red Book"). The amount of settled solids in the hopper(s) is measured by sounding after the pumping has stopped. A weighted disk attached to the end of a light line is used for the purpose. The standard disk is 6 inches in diameter, weighs 2 pounds 2 ounces and is assumed to rest at the top level of settled solids. Two or more soundings are measured in each hopper and the solid content thereof in cubic yards is read from a hopper capacity curve or from yardage tables prepared for the dredge. Simultaneously with the soundings, the mixture above the plane of settled solids is sampled. A special rig developed for this purpose, having a 1-quart bottle fitted with a stopper operated by an extension rod, is lowered to a point halfway between the top of each hopper load and the level of the settled solids. All samples thus obtained are thoroughly mixed to produce an average sample representing the percentage of material solids in the load. The yardage of solids in suspension in the load is computed by multiplying the hopper content less the settled portion by the average percentage of solids in suspension. The total volume of solids in the load is considered to be the sum of the volumes of settled solids and solids in suspension determined by the above procedure.

The Dutch Ministry of Transport and Public Works (Rijkswateraat) produced a sounding technique called the "half-ball and centrifuge" method to measure volumetric "payable quantities" (Rokosch 1989). The weight and volume (shaped like a hemisphere) of the sounding lead was designed to stop sinking at a level where the slurry density was $1,200 \text{ kg/m}^3$ (specific gravity of 1.2) or greater (called the settled solids). At least four soundings were taken and averaged together to define the 1.2 specific gravity horizon. The volume of settled solids was then determined from the hopper capacity chart. The volume of solids above this horizon (called the liquefied load) was calculated by retrieving slurry samples midway between the settled solids level and the surface of the slurry in the hopper, centrifuging them for a prescribed duration, and measuring the volume fraction of solids of the total sample. The volume of solids in the liquefied load was calculated by multiplying this volume fraction times the total liquefied load volume. The total volume of solids in the hopper was then calculated by adding the two solids' volumes together (settled and liquefied).

Rullens (1993) reports that the half-ball and centrifuge method has several advantages:

- Construction is simple.
- The system is essentially maintenance-free.
- The system can be made operational quickly.
- The system is inexpensive.
- Measurements are reasonably accurate.

Disadvantages of the half-ball and centrifuge method include:

- The contractor is not paid for increasing the load's density over 1.2 s.g.
- What the measured volume actually represents is not known.
- The liquefied load samples must be consolidated, so results are not immediately known, and feedback to optimize the loading process is not available.
- Results are affected by human influence.

Bin manual sounding methods.

Bin manual sounding measurement methods are similar to hopper manual sounding methods described above to determine the volume of dredged material being transported. One significant difference between sounding a hopper or bin is that cohesive sediment loaded by a mechanical dredge can be mounded up in the bin (Figure 3). With this situation, measurement error is related to the volume of material mounded above (or below) the averaged height of material calculated by multiple soundings of the bin.



Figure 3. Mounded dredged material in bin

Hopper level sensors. Hopper content volumes can also be measured by the use of level-sensing devices usually installed over the hopper (Figure 4). As with manual sounding, hopper material volume is calculated by applying the sensor-measured average material level to the hopper capacity table. Ultrasonic level-sensing sensors have been used by the dredging industry since the 1980's (Rokosch 1989). These hopper-level sensors consist of ultrasonic transducers that emit acoustic waves and detect the energy that's reflected from the dredged material surface. Similar to a hydrographic survey, the distance between the transducer and acoustic reflector is based on the time interval required for the acoustic energy to travel from the transducer, bounce off the hopper material, then return back to the transducer. Figure 5 shows an ultrasonic transducer mounted over the dredge *McFarland's* hopper. Two of these programmable sensors were mounted on each end of the *McFarland's* hopper as close to the hopper centerline as

possible to minimize trim-induced error (Welp and Rosati 2000). Sensor specifications state an accuracy of 0.25 percent of the measurement range (2 to 50 ft) with no temperature gradient. This measurement method's accuracy is affected by environmental factors (i.e., temperature, incident angle, surface composition, humidity, presence of nearby structures, and sediment buildup on the transducer by slurry spray).

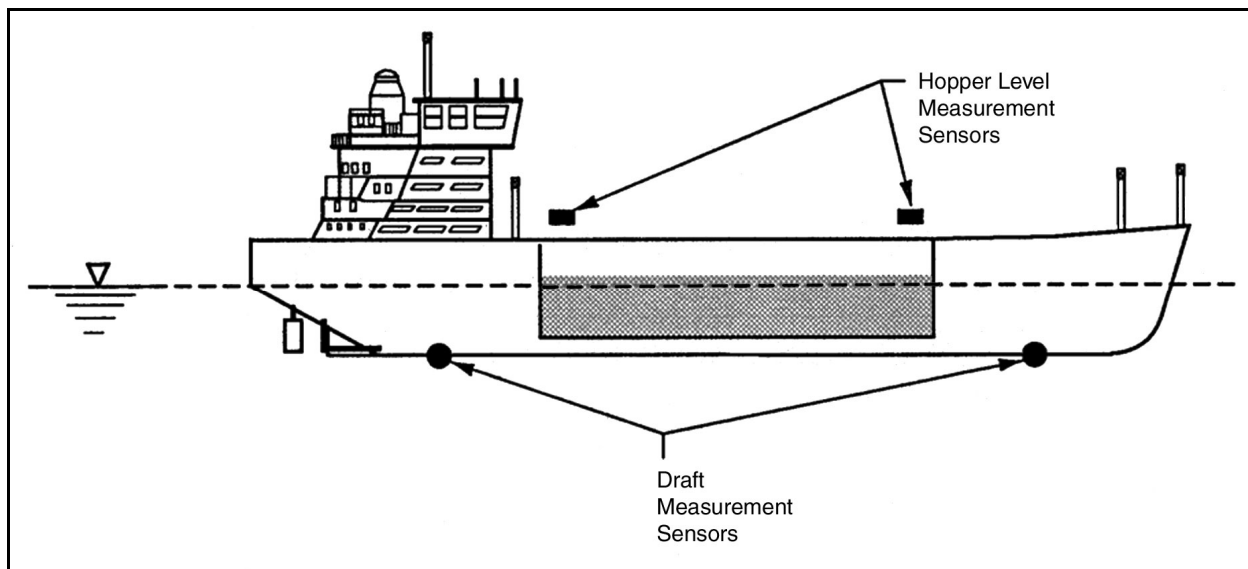


Figure 4. Hopper level and draft sensors

Experience on the *McFarland* and dredge *Wheeler* (Jorgeson and Scott 1994) illustrates that proper placement of these transducers is critical to optimizing operating efficiency and accuracy for these types of sensors. On both dredges, the sensors were located above the maximum hopper slurry level and away from the distribution points to minimize direct contact with splashing and spray. Hopper configuration aspects (i.e. being open or closed, sloping sides, etc.) and the presence of piping, auxiliary equipment, and structural members can impact placement alternatives of these sensors. Periodic cleaning of the transducers on the dredge *McFarland* assisted in minimizing error from sediment deposited on the transducer by spray, but when a sufficient layer of foam was generated on the slurry surface, inaccurate readings were recorded until the foam dissipated (this type of foam is illustrated in Figure 6). This error component has been observed on other dredges that use the Silent Inspector.

An additional measurement error component is introduced when using ultra-sonic sensors to measure sand load volumes with a layer of water overlaying the settled sand. The ultra-sonic pulse reflects off the supernatant water, not the sand surface, thereby introducing error proportional to the water layer's thickness. Another measurement error component is encountered when an uneven



Figure 5. An ultrasonic transducer mounted over the dredge *McFarland's* hopper

surface is created by sand in the hopper as shown in Figure 7. Hopper sounding methods are based on an averaged hopper load height. Sand volume is determined by averaging sand heights measured directly under the transducers. The amount of error introduced by this loading condition depends on the location and number of point measurements taken by sensors relative to the sand deposition pattern (unevenness of the load's surface and respective elevations under the sensors).



Figure 6. Foam generated on top of the hopper load



Figure 7. Uneven surface created by sand load in hopper

In Rotterdam, hopper dredges have used up to eight transducers in the hopper (two rows along starboard and port sides) to measure sand loads. With that many sensors, the various readings can be compared with each other and any signal that may show a large deviation compared to the average of all signals can be eliminated. Only the signals of the sensors that are all within a certain band are then averaged. The Dutch Rijkswaterstaat requires the use of ultrasonic level sensors for hopper level measurement for their Tonnes Dry Solids System. Other countries that use similar methods include the United Kingdom, Belgium, and Germany. These governments all require the use of ultrasonic sensors in their monitoring specifications. The various users have learned to deal with the inherent problems associated with sensors onboard hopper dredges, filtering and rejecting bad readings via software.¹

Bin level sensors. Ultrasonic sensors are also used to measure the level of dredged material in barges and scows. This method possesses measurement capabilities and limitations similar to those described above for hoppers, but additional complications can arise when a mechanical dredge loads the scow. The sensors risk damage from impact with the bucket when it's moving over (or in) the bin, or the sensors can be struck by material released from the bucket. Heaping of the material can also induce measurement error as described for the manual sounding bin measurement method (Figure 3).

Weight Measurement. Hopper and bin load weights are determined by measuring the entire vessel's loaded and unloaded weights, then subtracting the unloaded value from the loaded value. To accomplish this, the vessel's change in draft is measured and this measurement is converted into the volume of water displaced (displacement) from the curves of hydrostatic properties of the vessel's form (displacement curves). This displaced volume is then multiplied by the unit

¹ Personnel communication. 2004. Peter Dejong, Digital Automation and Control Systems, Inc., Houston, TX.

weight of water surrounding the hull to calculate the entire vessel weight. The earliest American hopper weight measurement system is documented in the “Yardage Meter Instruction Manual” (USACE 1959). The “Yardage Meter” used a “bubbler” draft system that measured the hydrostatic pressure at the dredge’s keel and converted this measurement into depth. The bubbler system is designed to maintain a constant flow of air to various “bubbling points” mounted by the keel. The pressure required to force the air out through the lines and bubbling points is equal to the hydrostatic pressure at the respective bubbling points. The hydrostatic pressure is then converted to depth, or draft, using the density of the water the vessel is immersed in (draft equals pressure divided by density of water). These bubbler systems are still used today, but the special 16-in.-diam pressure gauge with special dial used in the yardage meter has mostly been replaced by pressure transducers installed in the bubbler lines to measure the back pressures. Other draft measurement systems consist of pressure transducers mounted directly through the hull by the keel. These draft measurements are usually taken with at least two pressure sensors as shown in Figure 4, one mounted forward and one mounted aft on the underside of the vessel (Rokosch 1989). These sensors also measure the pressures (proportional to depth) experienced at the underside hull locations. Pressure sensors have also been used to measure bin load weights in the same manner as hopper dredges, or are manually measured by the draft markings on the hull.

Rokosch (1989) reports that advantages of the weight measurement system (a component of the Rijkswaterstaat’s Tons Dry Solids System) is that the system is independent of type of sediment and requires no manual actions, but the system measures weight from a relatively small difference in draft. The weight measurement component was reported to be used in maximum wave heights of 2 to 2.5 m.

Rullens (1993) reports that errors in this measurement method are introduced by:

- Incorrect positioning of draft sensors on the hull.
- Displacement not measured due to the vessel’s hull bending under the hopper load.
- Error due to use of the vessel’s displacement curve (to convert draft to vessel weight) without trim correction.
- Pressure measurement affected by pressure variations caused by vessel movement through water.
- Pressure measurements affected by wave action.
- Error induced by water density differences in converting hydrostatic pressure to draft.
- Non-linearity of pressure sensors.

Tons Dry Solids (TDS). TDS measures the hopper-load’s volume and weight in order to determine the quantity of “dry solids” that it contains. By applying the values for the dry solid’s specific density and the in situ water’s density in a formula with the hopper-load’s weight and volume (which indirectly measures the hopper-load’s average density), the total quantity of the dry solids can be calculated. Welp and Rosati (2000) describe this measurement method and the Corps’ initial experiences with it. Because the density is calculated by measuring both the weight and volume of the hopper or bin, the previously described volume and weight measurement technologies, and respective advantages/disadvantages and capabilities/limitations,

generally apply to TDS measurement. Additional requirements include incorporating the dry solid specific density and the in situ water density into the TDS equation.

TDS involves the measurement of the hopper-load's volume and weight in order to determine its average density and the quantity of "dry solids" that it contains. The equation used to calculate TDS is derived in Welp and Rosati (2000), as well as a more detailed description of TDS measurement. The data requirements for computing TDS are:

- Density of in situ water (ρ_w).
- Specific (or mineral) density of dry particles (ρ_m).
- Hopper volume (V_h).
- Hopper weight (W_h).

The in situ water and mineral densities are determined from representative samples collected from the dredging prism. The hopper volume and weight are measured by the methods previously described in this TN. How well TDS can be measured depends on how accurately and consistently the four factors presented above are measured, as well as the validity of the principals used to calculate it. The following sensitivity and uncertainty analyses illustrate the individual effects that each of these four factors have on TDS measurement accuracy.

TDS Sensitivity Analysis. A sensitivity analysis was conducted on the TDS equation using dredge *McFarland* as the presentation platform (TDS data were collected on the USACE dredge *McFarland*, see Welp and Rosati (2000) for details). The *McFarland* is a medium-sized hopper dredge with a rated hopper capacity of 2,400 m³ (3,140 yd³) and a loaded displacement (in fresh water) of 12,475 long tons. The sensitivity plot in Figure 8 graphically illustrates the relative effects that each of the four required data inputs (parameters) have on the final calculated TDS value on a hopper dredge of this size. In a sensitivity analysis, the value for each parameter is varied over a practical range of values while the other three TDS equation parameters are held constant. This process is then repeated for the other three parameters. For example, the mineral density curve in Figure 8 is plotted by holding the water density and hopper volume and weight parameters constant (1,250 kg/m³, 3,140 yd³, 2,834 long tons (LT), respectively), while the mineral density is varied from 2,600 kg/m³ to 2,800 kg/m³ (or specific gravities of 2.6 and 2.8, respectively). Sands and gravel range between 2,650 kg/m³ and 2670 kg/m³, while cohesive sediments such as silts and clays can vary from about 2,680 kg/m³ and 2750 kg/m³ (Scott 2000).

For the water density curve, this parameter is varied between 980 kg/m³ and 1030 kg/m³. Values of an average hopper density of 1,200 kg/m³ and full hopper volume of 3,140 yd³ were held constant for the mineral and water density curves. In the hopper (dredged material) volume curve, the volumes range "above and below" the most accurate, or "true" value of a full hopper of 3,140 yd³ and the hopper weight curve varies over a range of 500 LT.

Looking at the mineral density curve, when this parameter is varied between values typically encountered in the field of 2,650 kg/m³ and 2,750 kg/m³ (with respective calculated TDS values between 672 LT and 657 LT), the TDS value changes by about 15 LT. On the water density curve, when this parameter's (water density) value is varied from 980 LT to 1,030 LT, (with

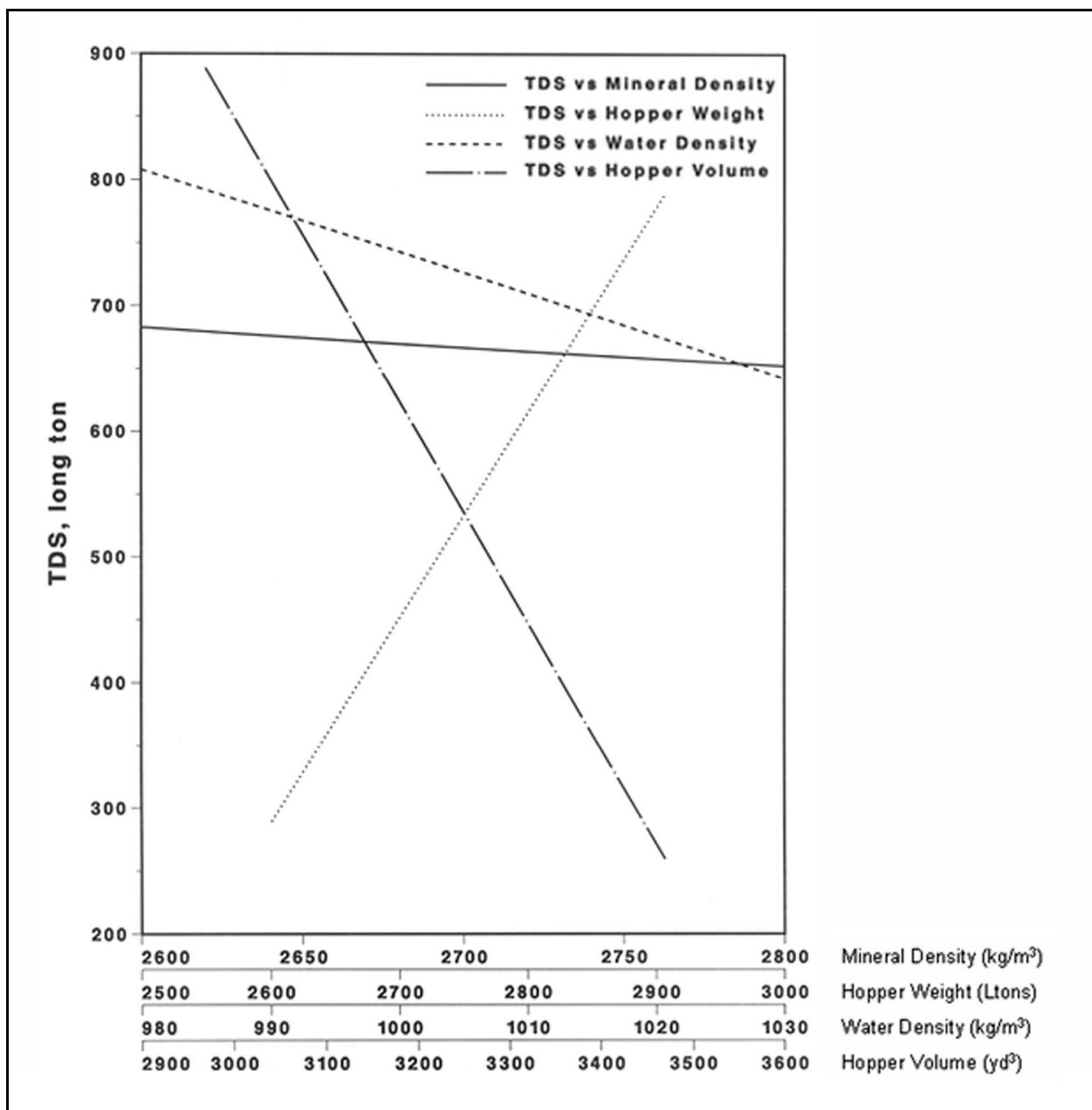


Figure 8. TDS sensitivity analysis

respective calculated TDS values of 805 kg/m³ and 640 kg/m³), the respective change in TDS is 165 LT. Given the mineral and water density ranges that are encountered in the field, it can be seen that mineral density value has the smallest effect on the final calculated TDS value.

On the hopper volume curve, by using the *McFarland's* ullage table/hopper volume relationship in the TDS equation, a change of 0.1 ft ullage equates to a change of approximately 16 LT TDS. For the hopper weight curve, application of the *McFarland's* draft/displacement relationship in the TDS equation produces a change of approximately 80 LT TDS per 0.1-ft change in draft. Evidently the draft measurement, which is used to determine the hopper content weight by

subtracting light ship displacement (weight) from loaded ship displacement, has the largest effect of the four variables in the TDS equation. As would be expected, if the hopper weight is over-estimated, the TDS value is likewise inflated, but when the hopper volume value is over-estimated, the TDS value is calculated below its “true” value.

Besides impacts on measurements being caused by the water density inside the hopper, the density of water surrounding the vessel can also impact TDS accuracy because of its influence on the vessel’s draft and respective displacement. The magnitude of this impact depends on whether this error is systemic or random in nature.

TDS Measurement Uncertainty. Each measurement and physical quantity associated with the calculation of dredging quantities has some error or uncertainty associated with it. The equation for calculating TDS production is a function of multiple variables (measurements and physical quantities), each contributing some error. These errors propagate through the data reduction equation to the final calculation. It is essential that the error associated with each variable is accounted for, and that the individual error contribution to the total error is recognized. Equations are introduced in Scott (2000) that describe production for both pipeline and hopper dredges. An uncertainty analysis expression is derived for each equation. Scott applies the general uncertainty analysis technique in a step-by-step manner to show the derivation of the uncertainty analysis expression. Example dredging situations are introduced in Scott (2000) to demonstrate the uncertainty analysis application. Numerical solutions show the error contribution of each variable, and the effect of uncalibrated instruments and unmeasured sediment and water properties on the accuracy of production calculations.

The results of Scott’s example uncertainty calculations for TDS (Table 1) show that the error potential is greatest for the case of poorly calibrated instruments (40 percent for Case 3), because the average density measured in the hopper is dependent on two measured variables. The water density contributes significant error when the instruments are properly calibrated. The error in hopper production calculations ranged from a low of about 10 percent for calibrated instruments and known sediment and water properties (Case 1), to over 40 percent for a worst case of uncalibrated instruments and unknown material properties (Case 4) (Scott 2000).

Table 1 Example Hopper Dredge Uncertainty Calculations¹					
Case	Mineral Density	Water Density	Hopper Volume	Hopper Weight	Total Uncertainty
1 ²	0.05	2.15	2.78	4.00	8.98
2 ³	0.22	11.26	1.62	2.33	15.43
3 ⁴	0.01	0.49	15.90	22.90	39.30
4 ⁵	0.08	4.21	15.15	21.81	41.25
¹ Information taken from Scott (2000). Percent uncertainty contributed by variable to total. ² Case 1 - All instruments calibrated and sediment properties measured. ³ Case 2 - All instruments calibrated and sediment properties estimated. ⁴ Case 3 - Instruments out of calibration and sediment properties measured. ⁵ Case 4 - Instruments out of calibration and sediment properties estimated.					

Scott presents this example only as a guide for applying the uncertainty analysis method for determining the accuracy of this type of production system calculation. It should be apparent

from these analyses that accurate instrument calibration, along with a thorough knowledge of the properties of the water, and to a much lesser degree mineral density, is necessary to ensure the highest degree of production measurement accuracy. This conclusion is also graphically illustrated in the sensitivity analysis plot.

In addition to the limitations previously described for hopper level sensors and the weight measurement method (both used to measure the average hopper load density), additional TDS measurement error can be induced by “dry” sand loading. The TDS equation is based on the density relationship between water and solids in a completely saturated slurry (water between all the solid particles). Fluid mud loads meet this criterion, but there are loading situations when the entire load is not saturated, such as with sand loads with unsaturated portions of the hopper load. These unsaturated portions can be due to an uneven loading surface (ridges) above the “water plane” (see Figure 7), or by water draining through the sand and out leaking seals, or over the weirs. As was shown in the sensitivity and uncertainty analyses above, measurements of the hopper volume and vessel’s draft (displacement) have the most effect on the accuracy of the final TDS calculated value. TDS measurement error is proportional to the volume of unsaturated dredged material (and respective absence of water in this volume).

SUMMARY: Research to improve dredging contract management, economics (cost optimization), and contaminated sediments management (document dredging and placement locations) is currently being conducted by the Innovative Technologies Focus Area of the DOER Program. This technical note describes currently used hopper and bin load measurement methods and analysis procedures and discusses their respective capabilities and limitations. Subsequent DOER technical notes from this Focus Area will refer back to this document as a basis for defining system requirements in the development of improved hopper and bin measurement technologies.

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